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DATE OF DEPOSIT: February 13, 2004

ELECTRON MICROSCOPES EXHIBITING IMPROVED IMAGING OF SPECIMEN HAVING CHARGEABLE BODIES

Cross Reference to Related Application

This application is a continuation of, and claims the benefit of, co-pending U.S. Patent application no. 09/583,001, filed on May 26, 2000. The entire '001 application is incorporated by reference into the instant application.

Field

This disclosure pertains to electron microscopes and related electron-optical systems with which it is possible to view a specimen surface in two dimensions.

Background

A scanning electron microscope (SEM) generally is used for examining the surface of a specimen, such as the product of a step in a process for manufacturing semiconductor integrated circuits, especially to ascertain the presence of surficial defects. In view of the fact that an electron beam is an exemplary charged particle beam, investigations have been made into the use of other charged particle beams (such as a focused ion beam) for similar applications.

Since principles generally applicable to an electron beam are applicable to an ion beam, the discussion below is made in the context of an electron-beam system. However, in view of the above, it will be understood that the invention is not limited to electron-beam systems.

In an SEM, as is known generally, an electron beam is irradiated onto a point on the surface of the specimen being observed. Impingement of the electron beam on the specimen surface causes the surface to emit secondary electrons. The secondary electrons are accelerated away from the surface, collected, and quantified by a suitable detector. To image a region on the sample, the electron beam simply is scanned in two dimensions in a raster manner. Secondary electrons generated at each irradiation point in the scan are collected and quantified. The data collected by

the detector are processed to form an image that is displayed on a screen (CRT) or the like.

A main disadvantage of conventional SEMs is the long period of time required for obtaining an image of the surface being observed. The time is related to the need to scan a point-focused electron beam two-dimensionally over the observed surface. As a result, "mapping electron microscopes" are being investigated for use, as a possible alternative to SEMs, in examining semiconductor wafers and chips and in other applications in which high speed is required. This is because a mapping electron microscope offers prospects of simultaneously viewing an entire region of the target surface in two dimensions. To such end, a mapping electron microscope utilizes an electron-optical system (*i.e.*, a system comprising a 2-dimensional projection-electron lens) to direct the electron beam onto an area of the sample surface that is larger than a point. Unfortunately, various technical problems remain unresolved with mapping electron microscopes.

An important technical problem (that is not limited to mapping electron microscopy) concerns electrostatic charging of the specimen surface that is being observed. Charging can occur at locations on the specimen occupied by insulators or floating conductors. During charging, the irradiated area acquires a positive or negative electrostatic charge whenever the number (quantity) of the electrons irradiating the specimen is not equal to the number (quantity) of electrons emitted from the irradiated surface as secondary electrons and the like. Whenever charging occurs, the observed surface of the specimen is not in a desired equipotential condition; in fact, the localized potentials within the observed field can differ to such an extent (due to localized accumulations of electrostatic charges) that imaging of certain regions is impossible.

In various types of scanning electron microscopes, including mapping electron microscopes, low-energy electrons, especially secondary electrons and the like, are accelerated and magnified to high magnification and projected by an electrostatic lens onto an imaging surface (*e.g.*, the surface of a detector). The energy band of such electrons that can be imaged is narrow due to defocusing (on-axis chromatic aberrations). Also, energy uniformity across the entire imaging field

is difficult to sustain. Serious problems can arise if the distribution of electrical potential varies greatly over the specimen surface because the image in the vicinity of such variations is distorted or cannot be formed at all, making accurate observation impossible. In addition, the specimen itself may be damaged if it becomes charged sufficiently greatly to cause an electrostatic discharge or insulation breakdown.

The occurrence of charging is determined at least in part by the "secondary-electron production efficiency." The secondary-electron production (SEP) efficiency is the current of produced secondary electrons divided by the beam current of charged particles in the beam irradiating the specimen. If the SEP efficiency is greater than unity (1), then the specimen acquires a positive electrostatic charge; if the SEP efficiency is less than unity, then the specimen acquires a negative electrostatic charge. Hence, to avoid the problems summarized above, it would be advantageous if specimen irradiation could be performed (especially with respect to insulators and floating conductors) in a manner by which the SEP efficiency is maintained as close to unity as possible.

However, a typical specimen (especially a patterned semiconductor wafer or chip) typically includes multiple types of insulators and floating conductors each having a different respective SEP efficiency. With such specimens, it is conventionally extremely difficult to observe the specimen by scanning or mapping electron microscopy without causing unacceptable levels of localized charging. Many specimens simply cannot be imaged at all without intentionally charging them at least to a certain extent (*e.g.*, to obtain a potential-contrast image). In such instances, it is difficult or impossible to control the extent of localized or general charging of the specimen.

Summary

The shortcomings of the prior art as summarized above are solved by electron microscopes as disclosed herein in which the degree of localized charging of the specimen is controlled, especially with respect to insulators and floating conductors. Hence, the charging is maintained between a minimum needed for producing a

viewable image and a maximum beyond which a viewable image is not obtainable with sufficiently low distortion or without damaging the specimen.

A representative embodiment of an electron microscope comprises an irradiation-optical system situated and configured to irradiate a two-dimensional region of a surface of a specimen with a beam of charged particles produced by a charged-particle source. The irradiation of the region causes emission of imaging electrons from the irradiated region. The embodiment also includes an imaging-electron detector having a detection surface. The embodiment also comprises an imaging-electron-optical system situated and configured to direct the imaging electrons onto the detection surface, wherein the irradiation-optical system controls the beam of charged particles in such a manner that changes in potential in the irradiated region due to charging by the charged particles are within a range in which an image can be obtained.

The imaging optical system further can be configured to irradiate multiple regions on the specimen surface such that the regions acquire respective changes of surface potential (U_s) that are greater than respective minimum changes of surface potential (U_{min}) needed to produce a viewable image and respective maximum changes of surface potential (U_{max}) beyond which a viewable image cannot be obtained. A Wien filter can be included to direct the beam of charged particles from the irradiation-optical system to the specimen surface. Using a Wien filter allows for perpendicular irradiation of the specimen, which facilitates uniform irradiation of the specimen, compared to angled irradiation. Koehler illumination conditions can be created by placing an aperture between the Wien filter and the specimen, and aligning the focal point of a cathode lens (located between the aperture and the specimen) with the aperture position.

The detector can include an imaging-electron converter and a photoelectric converter, such as a charged-coupled device (CCD). The detector receives the imaging electrons and converts them to a corresponding electrical signal.

Desirably, irradiation of the region of the specimen surface is performed under uniform irradiation conditions. This produces a clear image without lightening

or darkening of the image based on localized charging or irradiation irregularities within the region.

Also provided are methods for performing electron microscopy of a surface of a specimen. An embodiment of such a method comprises placing the specimen relative to an irradiation-optical system and irradiating a two-dimensional region of a surface of the specimen with a beam of charged particles that have propagated from a source through the irradiation-optical system. The irradiation is performed so as to cause emission of imaging electrons from the irradiated region on the specimen. The imaging electrons are directed to a detection surface of an imaging-electron detector. Operation of the irradiation-optical system is controlled so as to control the beam of charged particles in a mannner such that changes in potential in the irradiated region due to charging by the charged particles in the region of the specimen surface are within a range in which an image is obtained.

The foregoing and additional features and advantages of the invention will be more readily apparent from the following detailed description, which proceeds with reference to the accompanying drawings.

Brief Description of the Drawings

FIG. 1 is a schematic elevational section showing exemplary insulator bodies in a specimen irradiated with a single electron beam for mapping electron microscopy.

FIGS. 2(a)-2(b) are respective graphs of representative relationships between incident energy (of an electron beam) and secondary-electron production efficiency of respective insulator bodies such as shown in FIG. 1.

FIG. 3 is a schematic elevational section showing exemplary insulator bodies in a specimen irradiated with multiple electron beams for mapping electron microscopy.

FIGS. 4(a)-4(b) are respective graphs of representative relationships between incident energy (of an electron beam) and secondary-electron production efficiency of respective insulator bodies such as shown in FIG. 3.

FIG. 5 is a schematic optical diagram of a mapping electron microscope according to a first representative embodiment.

FIG. 6 is a schematic optical diagram of a mapping electron microscope according to a second representative embodiment.

FIG. 7 is a schematic optical diagram of a mapping electron microscope according to a third representative embodiment.

Detailed Description

General Considerations

As noted above, a typical specimen for electron microscopy includes multiple individual insulator bodies and conductors. The respective change of surface potential (U_s) of each such body or region desirably is controlled so that the potential is between a minimum change in surface potential (U_{min}) needed to produce a viewable image and a maximum change in surface potential (U_{max}) beyond which a viewable image cannot be obtained (due, for example, to the image having excess distortion or the specimen being damaged by electrostatic discharge). Also, irradiation of the specimen desirably is performed under uniform illumination conditions within the imaging field to facilitate obtaining a clear image without localized lightening or darkening from respective localized charging or irradiation irregularities within the field.

As used herein, "imaging electrons" are electrons emitted from the specimen or other surface due to irradiation by a charged particle beam. Imaging electrons include, for example, reflected electrons, secondary electrons, and backscattered electrons.

The changes of surface potentials noted above desirably have the following relationship for optimal imaging:

$$U_{min} < U_s < U_{max} \quad (1)$$

The efficiency with which imaging electrons are emitted from an irradiated region of the specimen is a function of the energy of the irradiating electrons (or other charged

particles), the substance and structure of the specimen, the imaging environment, and other factors.

Most substances used in semiconductor-fabrication processes have a secondary-electron production (SEP) efficiency greater than unity (1) in irradiating-electron fields of 100 eV to 1 KeV, but less than unity in fields outside this range. Also, whenever a floating conductor or insulator is irradiated for a period of time, the conductor or insulator accumulates charge and exhibits a corresponding change in potential over time. If the specimen has only one type of floating conductor or insulator, and if the specimen is uniform, then the specimen can be irradiated readily with a single beam having an energy that will yield a SEP efficiency of unity. However, if the specimen comprises multiple types of substances (which is the case with most semiconductor wafers and chips), then the irradiation energy that will yield a SEP efficiency of unity typically will differ for each of the constituent substances. Under such conditions, optimal imaging of all regions of the specimen surface usually cannot be performed using a single beam having a single energy level. Either multiple beams are required (each having a respective energy level), or a single beam with multiple energy levels is required.

For example, consider a specimen having an elevational sectional profile as shown in FIG. 1, in which regions 2, 3 are respective insulator bodies A and B in a silicon substrate 1. The substrate 1 is electrically conductive whereas the insulator bodies A, B are not. The top surface of the specimen is irradiated (arrows 4) by incident electrons within an illumination field with the intention of producing an image of the specimen surface. Because the specimen in this example has a planarized top surface (as achieved by a suitable technique such as CMP), image contrast generally will be too low for obtaining a good image by optical microscopy or even by edge-emphasized SEM microscopy.

Upon illuminating the FIG.-1 specimen with electrons 4 having an incident energy of V_1, localized charging occurs that tends to change the incident energy of electrons on regions undergoing localized charging. To the extent that there is no leakage current, the incident energy on the insulator bodies A, B shifts from the initial value of V_1 to respective levels “a” and “b” as shown in FIGS. 2(a)-2(b),

respectively. The levels "a" and "b" correspond to respective SEP efficiencies of the respective insulator bodies A and B at irradiation equilibrium. As a result, the change of (shift in) the charging potential of the insulator bodies A ($U_{s/A}$) and the change of (shift in) the charging potential of the insulator body B ($U_{s/B}$) increases by ($a - V_1$) and ($b - V_1$), respectively.

The shifts in charging potentials $U_{s/A}$ and $U_{s/B}$ simultaneously may fulfill the following two inequalities:

$$U_{min} < U_{s/A} < U_{max} \qquad (2)$$

$$U_{min} < U_{s/B} < U_{max} \qquad (3)$$

(Note that, above, U_{min} and U_{max} are the same for each body A and B.) However, there generally are many instances in which these conditions cannot be achieved, even if the respective levels of V_1 are changed in FIGS. 2(a) and 2(b).

Now, assume that the specimen is irradiated simultaneously with electrons 4 having an incident energy of V_1 and electrons 5 having an incident energy of V_2, as shown in FIG. 3. V_1 and V_2 are selected so as to be situated on opposite sides of the equilibrium points a and b of the respective insulator bodies A and B, as shown in FIGS. 4(a) and 4(b), respectively. The respective shifts in charging potential $U_{s/A}$, $U_{s/B}$ of the insulator bodies A and B, irradiated with the electrons of two different energies V_1, V_2, are found as follows.

The SEP efficiency functions for the insulator bodies A and B, as functions of the irradiation electron energy V, are denoted FA(V) and FB(V), respectively. The respective irradiation-electron beam currents at the specimen surface of the beams having respective incident energies of V_1 and V_2 are I_1 and I_2, respectively. The respective secondary-electron beam currents emitted from the surfaces of the respective insulators A and B when irradiated at the respective incident energies V_1 and V_2 are expressed as:

$$\text{from A:} \quad I_1 \cdot FA(V_1) + I_2 \cdot FA(V_2) \qquad (4)$$

$$\text{from B:} \quad I_1 \cdot FB(V_1) + I_2 \cdot FB(V_2) \qquad (5)$$

As can be seen, the respective sums indicated in Expressions (4) and (5) generally are not the same as the sum of the incident irradiation-beam currents:

$$I_1 + I_2 \quad (6)$$

Rather, in Expressions (4) and (5), each of the I_1 and I_2 terms is factored by the respective SEP efficiency (FA) function. As a result, charging of the respective insulator bodies occurs until equilibrium is reached. At equilibrium, the incident energy V_1 is shifted to $V_1 + U$ by the charge-up potential U, and the respective shifts in surface potential $U_{s/A}$, $U_{s/B}$ reach the following respective steady-state conditions:

$$\text{for A:}\quad I_1 + I_2 = I_1 \cdot FA(V_1 + U_{s/A}) + I_2 \cdot FA(V_2 + U_{s/A}) \quad (7)$$

$$\text{for B:}\quad I_1 + I_2 = I_1 \cdot FB(V_1 + U_{s/B}) + I_2 \cdot FB(V_2 + U_{s/B}) \quad (8)$$

If the variable α is denoted as follows:

$$\alpha = I_1/(I_1 + I_2) \quad (9)$$

then Equations (7) and (8) can be written respectively as:

$$\text{for A:}\quad 1 = \alpha \cdot FA(V_1 + U_{s/A}) + (1 - \alpha) \cdot FA(V_2 + U_{s/A}) \quad (10)$$

$$\text{for B:}\quad 1 = \alpha \cdot FB(V_1 + U_{s/B}) + (1 - \alpha) \cdot FB(V_2 + U_{s/B}) \quad (11)$$

If $U_{s/A}$ and $U_{s/B}$ and one of α, V_1, and V_2 are established at specific values that fulfill Expressions (2) and (3), then the remaining two variables can be determined so that both Equations (10) and (11) are satisfied, thereby allowing the specimen to be imaged with good results. Moreover, by changing the total irradiation-current density, illumination can be accomplished under even better irradiation conditions because the image is brightened.

As can be ascertained from the foregoing, if α, V_1, and V_2 in Equations (10) and (11) are all found as variables, then the respective values can be applied to up to three types of insulators. (For example, for a third insulator FC(V) experiencing a shift in charging potential $U_{s/C}$, $1 = \alpha \cdot FC(V_1 + U_{s/C}) + (1 - \alpha) \cdot FC(V_2 + U_{s/C})$.) Since the number of new variables increases by two (*i.e.*, an additional incident-energy (V) term and an additional beam-current (I) term is added) for each additional beam supplying another level of irradiation electron energy, the number of types of insulators to which these principles can be applied also increases by two under such conditions. (*I.e.*, each beam has two variables V and I. Simultaneous equations involving these variables have two solutions.)

Hence, the irradiation-optical system can be configured such that the specimen being observed is irradiated simultaneously by illumination from multiple electron sources each having a respective current (I) and incident energy (V) that are controlled independently, as described above. The respective currents and incident energies can be established to maintain the changes in the surface potential due to charging within respective target values for each insulator or floating conductor. This allows the surface potential (U_s) due to charging to be controlled for each insulator and/or floating conductor so that the surface potential is between a minimum amount (U_{min}) needed to view an image and a maximum amount (U_{max}) beyond which a viewing image cannot be obtained with low distortion and/or without damaging the specimen itself.

The invention is further described below in the context of representative embodiments that are not intended to be limiting in any way.

Representative Embodiment 1

This embodiment, depicted in FIG. 5, comprises irradiation-beam columns 11, 12, a Wien filter (E×B) 13, a cathode lens 14, a projection-optical system 16, and a detection surface 17 (*e.g.*, surface of a suitable detector of secondary electrons). The specimen surface is denoted by the numeral 15.

The irradiation columns 11, 12 accelerate electrons from respective electron sources 11S, 12S and form the electrons into respective beams of predetermined

respective transverse profile and area. The irradiation column 11 is situated at a respective angle θ_1 to the optical axis AX, and the irradiation column 12 is situated at a respective angle θ_2 to the optical axis AX. The respective irradiation beams propagate to the optical center of the Wien filter 13. Each irradiation beam is deflected by the Wien filter 13 to propagate along the axis AX toward the specimen surface 15. Hence, the irradiation beams are incident perpendicularly to the specimen surface 15. The irradiating electrons in the irradiating beams are decelerated by a retarding voltage applied by the cathode lens 14 and are incident onto a predetermined area of the specimen surface 15.

An aperture (not shown) desirably is situated between the Wien filter 13 and the cathode lens 14. By locating the aperture at the focal point of the cathode lens 14, the aperture serves to Koehler-irradiate the specimen surface 15.

In the following discussion, the irradiation beams entering the Wien filter 13 from the irradiation columns 11, 12 have respective energies of V_{11} and V_{12}, and respective incident energies V_1 and V_2. The potential energy imparted to the respective irradiation beams by the retarding voltage imposed by the cathode lens 14 is denoted V_{ret}. The potential energy V_{ret} can be positive or negative relative to the specimen surface 15, but normally is positive. The energies V_{11} and V_{12} are expressed as, respectively:

$$V_{11} = V_1 + V_{ret} \qquad (12)$$

$$V_{12} = V_2 + V_{ret} \qquad (13)$$

The respective beam-current values of the irradiation beams from the respective columns 11, 12 are denoted I_1 and I_2, which are related to V_1, V_2, and α (= $I_1/(I_1 + I_2)$) as set forth in Equations (10) and (11).

The respective deflection angles θ_1 and θ_2 of the irradiation beams are established simultaneously according to the following:

$$L = (\sin\theta_1/eB)(2m)^{1/2}V_{11}/[(V_{11})^{1/2} + (V_{ret})^{1/2}] \qquad (14)$$

$$L = (\sin\theta_2/eB)(2m)^{1/2}V_{12}/[(V_{12})^{1/2} + (V_{ret})^{1/2}] \qquad (15)$$

within a magnetic field B that fulfills Wien conditions with respect to the secondary electrons accelerated at a retarding voltage of V_{ret}, wherein "L" is the nominal thickness of the Wien filter 13, "e" is the absolute value of the charge of an electron, and "m" is the mass of an electron. At known respective energies V_{11}, V_{12}, the deflection angles θ_1, θ_2 can be set to any value that satisfies the relation:

$$\sin\theta_1/\sin\theta_2 = V_{12}[(V_{11})^{1/2} + (V_{ret})^{1/2}]/\{V_{11}[(V_{12})^{1/2} + (V_{ret})^{1/2}]\} \qquad (16)$$

If the deflection angles θ_1, θ_2 are set accordingly, then the incident energies can be selected in satisfaction of Equation (16). It is possible to vary the respective irradiation-current densities randomly by changing the parameters of the respective electron sources 11S, 12S and irradiation columns 11, 12.

<u>Representative Embodiment 2</u>

This embodiment is shown in FIG. 6, and includes a second Wien filter 18. All other components in this embodiment are similar to corresponding components in the FIG.-5 embodiment and have the same respective reference numerals. Irradiation electrons from the irradiation column 11 and irradiation electrons from the irradiation column 12 enter the separate Wien filters 13, 18, respectively. Consequently, in this embodiment, the magnetic fields B in Equations (14) and (15) are independent. This configuration makes it possible to change the electron energies of the various irradiation systems independently. The respective irradiation-current densities can be varied randomly by changing the parameters of the respective electron guns and irradiation columns.

<u>Representative Embodiment 3</u>

This embodiment is shown in FIG. 7. Irradiation electrons from the irradiation column 11 and irradiation electrons from the irradiation column 12 are irradiated at respective angles from the optical axis AX of the imaging system. Consequently, the respective electron energies of the various irradiation systems can

be changed independently. The respective irradiation-current densities can be varied independently by changing the parameters of the respective electron guns and of the respective irradiation columns. However, with this embodiment, uniform illumination over the entire field is more difficult than with a perpendicular illumination scheme such as those of FIGS. 5 and 6.

In each of the representative embodiments described above, only two irradiation columns 11, 12 are provided. However, greater numbers of irradiation columns can be utilized. Increasing the number of irradiation columns makes it possible (especially when there are numerous types of insulators in or on the specimen surface 15) to impart changes in surface potential for each insulator body by appropriately charging them up.

In addition, although not shown, an effect similar to parallel illumination from the multiple irradiation columns 11, 12 can be obtained using only one irradiation column that produces a beam of which the beam current and incident energy are changed periodically in a repeating manner in serial time segments. This scheme can be utilized because charging is a phenomenon that occurs overlappingly in time and space.

Whereas electron beams are utilized as the irradiating beams in each of the representative embodiments described above, it will be understood that irradiation can be performed with equal facility using another type of charged particle beam such as an ion beam.

Whereas the invention has been described in connection with multiple representative embodiments, it will be understood that the invention is not limited to those embodiments. On the contrary, the invention is intended to encompass all modifications, alternatives, and equivalents as may be included within the spirit and scope of the invention, as defined by the appended claims.